Discrepancy of complete-arch titanium frameworks manufactured using selective laser melting and electron beam melting additive manufacturing technologies

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Abstract: STATEMENT OF PROBLEM Titanium frameworks for implant-supported prostheses can be additively manufactured using different powder-based fusion technologies, including selective laser melting (SLM) and electron beam melting (EBM). Some manufacturers have developed a technique that combines the printing of the framework with the subsequent machining of the implant interface. Whether these technologies produce frameworks with acceptable accuracies is unclear. PURPOSE The purpose of this in vitro study was to evaluate the discrepancy obtained from the digitizing procedures of the definitive cast, the implant-prosthesis discrepancy, and the distortion of the manufacturing processes in the fabrication of titanium frameworks for implant-supported complete-arch prostheses manufactured using SLM and EBM additive manufacturing technologies. MATERIAL AND METHODS A completely edentulous mandibular definitive cast with 4 implant analogs and a replica of a screw-retained interim restoration was obtained. A standard tessellation language (STL) file of the framework design was prepared using dental software (Exocad). Six frameworks were manufactured using either SLM (3D Systems) or EBM (Arcam) technologies. Discrepancy (m) was measured at the x- (mesiodistal), y- (buccolingual), and z- (occlusogingival) axes by using the formula 3D=x+y+z three times by best-fit superimposure of the definitive cast STL file, the definitive cast titanium framework, and the framework STL file by using a coordinate measuring machine (CMM) controlled by software (Geomagic). The Kruskal-Wallis and Mann-Whitney U statistical tests were used (=.05). RESULTS The digitizing procedures of the definitive cast showed a mean accuracy of 3 ±3 m. Except for the z-axis (P<.05), no significant differences were observed between the SLM and EBM technologies for implant prosthesis discrepancy for the x- or y-axis (P>.05). The most favorable results were obtained in the z-axis, representing the occlusogingival direction. Three-dimensional discrepancy measurements in all comparisons ranged between (60 ±18 m and 69 ±30 m) and were not statistically significant (P>.05). The highest discrepancy was observed in the y-axis (37 to 56 m), followed by the x- (16 to 44 m) and z- (6 to 11 m) axes (P<.05). CONCLUSIONS The titanium frameworks analyzed for a complete-arch implant-supported prosthesis fabricated using either the SLM or EBM additive technologies showed a clinically acceptable implant-prosthesis discrepancy, where similar discrepancies on the x-, y-, and z-axes were found between the additive manufacturing technologies. Both technologies showed comparable abilities to manufacture the STL file additively on the x-, y-, and z-axes.

DOI: https://doi.org/10.1016/j.prosdent.2018.02.010

Originally published at:
Revilla-León, Marta; Ceballos, Laura; Martínez-Klemm, Iñaki; Özcan, Mutlu (2018). Discrepancy of complete-arch titanium frameworks manufactured using selective laser melting and electron beam melting additive manufacturing technologies. Journal of Prosthetic Dentistry, 120(6):942-947.
DOI: https://doi.org/10.1016/j.prosdent.2018.02.010

TITLE

Discrepancy of complete-arch, titanium frameworks manufactured using selective laser melting and electron beam melting additive manufacturing technologies

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Awarded with the research grant of the Spanish Association for Prosthodontics and Aesthetics (Sociedad Española de Protesis y Estética - SEPES).

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KEYWORDS

3D printing, Additive manufacturing technologies, Electron Bean Melting, Selective Hybrid Prostheses, Laser Melting, Titanium.

ACKNOWLEDGEMENT

To the Spanish Association for Prosthodontics and Aesthetics (Sociedad Española de Protesis y Estética - SEPES) for the research grant awarded to this project.

CONFLICTS OF INTEREST

The authors declare no conflict of interests with the materials used on this study.

JPD-17-089

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ABSTRACT

Statement of problem. Titanium frameworks for implant-supported prostheses can be additively manufactured using different powder-based fusion technologies, including selective laser melting (SLM) and electron beam melting (EBM). Some manufacturers have developed a technique that combines the printing of the framework with the subsequent machining of the implant interface. Whether these technologies produce frameworks with acceptable accuracies is unclear.

Purpose. The purpose of this in vitro study was to evaluate the discrepancy obtained from the digitizing procedures of the definitive cast, the implant-prosthesis discrepancy, and the distortion of the manufacturing processes in the fabrication of titanium frameworks for implant-supported complete-arch prostheses manufactured using SLM and EBM additive manufacturing technologies.

Material and methods. A completely edentulous mandibular definitive cast with 4 implant analogs and a replica of a screw-retained interim restoration was obtained. A standard tessellation language (STL) file of the framework design was prepared using dental software (Exocad). Six frameworks were manufactured using either SLM (3D Systems) or EBM (Arcam) technologies. Discrepancy (µm) was measured at the x- (mesiodistal), y- (buccolingual), and z- (occlusogingival) axes using the formula $3D = \sqrt{x^2 + y^2 + z^2}$ three times by best-fit superimposure of the definitive cast-STL file, the definitive cast-titanium framework, and the framework-STL file using coordinate measuring machine (CMM) controlled by software (Geomatic). The Kruskal Wallis and Mann-Whitney U statistical tests were used (α=.05).

Results. The digitizing procedures of the definitive cast showed a mean accuracy of 3 ±3 μm. Except for the z-axis (*P*<.05), no significant differences were observed between the SLM and EBM technologies for implant prosthesis discrepancy for the x- or y-axis (*P*>.05). The most favorable results were obtained in the z-axis, representing the occlusogingival direction. Three-dimensional (3D) discrepancy measurements in all comparisons ranged between (60 ±18 μm and 69 ±30 μm) and were not statistically significant (*P*>.05). The highest discrepancy was observed in the y- (37 to 56 μm), followed by the x- (16 to 44 μm) and the z- (6 to 11 μm) axis (*P*<.05).

Conclusions. The titanium frameworks analyzed for a complete-arch implant-supported prosthesis fabricated using either the SLM or EBM additive technologies showed a clinically acceptable implant-prosthesis discrepancy, where similar discrepancies on the x-, y- and z-axes were found between the AM technologies. Both AM technologies showed comparable abilities to manufacture the STL file additively on the x-, y-, and z-axes.

CLINICAL IMPLICATIONS

Titanium frameworks for complete arch implant-supported prosthesis fabricated using either selective laser melting (SLM) or electron beam melting (EBM) additive technologies obtained a clinically acceptable implant-prosthesis discrepancy.

INTRODUCTION

Attempts have been made to determine an acceptable level of implant-prosthesis discrepancy.[1-3] Brånemark[1] defined passive fit by proposing that a maximum 10-μm discrepancy enabled bone maturation and remodeling in response to occlusal loads. Klineberg and Murray[2] advocated that metal frameworks presenting discrepancies greater than 30 μm over more than 10% of the circumference of the abutment interface were unacceptable. Jemt[3] defined passive fit as a discrepancy that did not cause any long-term clinical complications and reported discrepancies smaller than 150 μm as acceptable. An unacceptable level of framework misfit was considered to exist when greater than half-a-turn was needed to completely tighten the gold screw after its initial seating resistance was encountered.[3] Although the preceding values were reported and subsequently often cited, they are empirical.[4] Nevertheless, the accuracy of the fit between the implant frameworks and the underlying structures is a critical factor in minimizing the biological and mechanical complications of an implant-supported prosthesis.[5-11]

The implant-prosthesis discrepancy produced by conventional casting procedures or computer numeric control (CNC) machining have been studied.[12-27] The range of the discrepancy reported varied, depending on the connection design,[14] the number of units in the framework,[21-26] and the x-, y-, and z-axes evaluated.[21-26]

The digital workflow for the fabrication of a metal framework is composed of 3 fundamental steps: data acquisition, data processing, and manufacturing.[28,29] Data acquisition consists of the measurement of the 3-dimensional (3D) surface contours of the oral structures and transforms it into digital data sets. This process is achieved through a digitizing device such as an intraoral scanner, a computed tomography (CT) image, or an extraoral scanner.[30,31] The procedure used to scan and transfer the implant position influences the fit accuracy of the computer-aided design and computer-aided manufacturing (CAD-CAM) framework.[32,33]

Data processing involves calculations from mathematical algorithms to remove the aberrant points obtained by the digitizer and optimize the density of the point cloud information and the processes to design a restoration with CAD software.[31,34] When this process is completed, a standard tessellation language (STL) file is obtained.[28,34]

The manufacture of the metal framework can be accomplished through additive or subtractive technologies.[35] Three-dimensional metal printing or additive manufacturing (AM) technologies are recently developed options to conventional casting and milling procedures in prosthodontics. The American Society for Testing and Materials (ASTM) international committee defined AM as ‘‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”.[29]

The ASTM has also determined 7 AM categories: stereolithography (SLA), material jetting, material extrusion, binder jetting, powder bed fusion (PBF), sheet lamination, and direct energy deposition.[36] PBF technologies are the most common used for 3D metal printing in dentistry. Three types of PBF technologies have been introduced, namely selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM).[36-38]

With SLS technology, laser energy is used to heat and consolidate metal powder layer upon layer.[39] Typically, the resulting parts are only sintered but they demonstrate adequate mechanical properties for many applications.[40-44] Achieving the melting point during the additive manufacturing process is a critical step that differentiates the PBF technologies; only the SLM and EBM technologies fully melt the metal powder.[36,39,45-47] The main differences between these technologies are the energy source (fiber lasers, Nd:YAG lasers, or electron beam),[47-51] energy power (100 to 500 W to 7 kW),[46,49,51] chamber condition (argon, nitrogen, or helium),[46,49,51] temperature reached,[46,49-51] layer thickness (10 to 50 μm)[50,51] and grain size (20 to 105 μm).[50,51]

Studies that evaluated components obtained through these additive manufacturing procedures concluded that their mechanical properties are better than those obtained using conventional casting procedures.[51-55] Moreover, the authors concluded that AM technologies delivered equal or slightly improved mechanical properties than milled metal.[51-55]

To achieve a precise implant interface, techniques have been developed that combine the PBF technologies with subsequent CNC machining of the implant interface. These technologies require knowledge on how to work from the printer to the milling machines without losing accuracy.

The Mylab (Esaote) measurement system based on stylus contact technique has been developed to analyze the implant-prosthesis discrepancy.[55-58] The system is linked to a computer for geometric transformations and calculations, statistical data analysis, and graphic displays of the collected information. This technique uses a coordinate measurement machine (CMM) linked to a computer to fit theoretically calculated surfaces to each other by means of the least-square method. These calculations locate the center of a component and its long axis. The center point is projected along the long axis of the component to a point on the component-bearing surface mean z axis plane, which is defined as the centroid point. Any misfit between a mating pair of centroid points is described by 3 space directions (x-, y-, and z-axis).[58] The best fit between these centroid points for the implant/abutment replicas and the framework is achieved by translating and rotating the several data sets with the computer; the least misfit is determined according to the least-square method as reported by Gauss.[55,58-60] The CMM analysis is widely used in dentistry to evaluate implant-prosthesis fit in the x-, y-, and z-axes.[12,13,56,57-60]

The purpose of this in vitro study was to evaluate the discrepancy obtained from the digitizing procedures of the definitive cast, the implant-prosthesis discrepancy, and the distortion of the manufacturing processes when fabricating titanium frameworks for implant-supported complete arch prostheses manufactured using SLM and EBM AM technologies. The null hypotheses tested were that the 3D discrepancy within each x-, y-, and z-axis would be similar between the definitive cast and the STL file; between the definitive cast and the titanium frameworks fabricated using SLM and EBM technologies; and between the STL file and the titanium frameworks fabricated using SLM and EBM technologies.

MATERIAL AND METHODS

A patient's edentulous mandibular definitive cast was modified with 4 implant replicas (RN synOcta analog, grey with red stripe; Straumann) and a replica of a screw-retained interim restoration made from non-reflective acrylic resin (PalapressVario; Kulzer GmbH) (Fig. 1A). A contact (Renishaw DS10 Scanner; Renishaw) and an optical (Renishaw DS20; Meditec) scanner and dental CAD software (Exocad Dental CAD; Exocad GmbH) were used to design the metal framework and obtain the STL file. The same STL file was used to fabricate all the metal frameworks.

Two groups were established: the EBM group; complete arch titanium (Ti6Al4V ELI Metal powder; Arcam) implant frameworks fabricated using an electron beam meting AM technology (Arcam Q2; Arcam AB) (Fig. 1B) and the SLM group; complete arch titanium (Rematitan Metal powder; Concept Laser) implant frameworks fabricated through a selective laser melting AM technology (Dentwise-Layerwise; 3D systems) (Fig. 1C). The composition of the metal powder and the mechanical properties of the AM titanium is presented in Tables 1 and 2. A total of 6 metal frameworks were produced having 3 specimens per group, 4 implants per specimen.

A CMM machine (Zeiss; Carl Zeiss Industrielle Messtechnik GmbH, accuracy 1 μm in all axes) was used to evaluate the discrepancy at the implant-prosthesis interface by an independent laboratory (Laboratorio de Ingieneria Dimensional S.L.) (Fig. 2). In brief, the definitive cast was measured and used as a reference for comparison of the 6 different frameworks for each implant replica.[49]

Before measuring, the definitive cast and the frameworks were placed in a mold seated on a reinforced-concrete table. The data for each implant replica was calculated locating the center point of each implant replica in 3 dimensions by measuring different points on the most coronal part by mapping the x-, y-, and z- axes with a 0.5-mm contact stylus and a light force of 0.1 N.

These data were used to analyze the 3D x-, y-, and z-axes and for each individual implant replica, and the 3D discrepancy using the formula $3D = \sqrt{x^2 + y^2 + z^2}$ and the best-fit technique with software (Geomatic; Geomatic GmbH). Each measurement was repeated 3 times.

Three comparisons were calculated: between the definitive cast and the STL file, representing the distortion obtained from the digitizing of the conventional stone cast using the laboratory dental scanner; between the AM frameworks with the definitive cast representing the implant-prosthesis discrepancy; and between the STL file and the AM frameworks representing the ability of the manufacturing process to replicate the digital framework design.

The normal distribution of the values obtained for the x-, y- and-z axes as well as for the 3D discrepancy was explored by the Shapiro-Wilk test. Since the results were not normally distributed, the nonparametric Kruskal–Wallis test followed by the Mann–Whitney U test for pairwise comparisons were applied using statistical software (IBM SPSS Statistics v22; IBM Corp) (α=.05).

RESULTS

Table 3 shows the calculated distortion between the definitive cast and the STL file, representing the discrepancy obtained from the digitizing procedures of the definitive cast. Similar results were found for the implant prosthesis discrepancy measurements and for the manufacturing process distortion when replicating the digital design of the AM framework (Table 4). Except for the z-axis (P<.05), no significant differences were detected between the SLM and EBM technologies (P>.05). Three-dimensional accuracy measurements in all comparisons ranged between (60 ±19 and 69 ±30 µm) (P>.05). The highest discrepancy was observed in the y-axis (37 to 56 µm), followed by the x-axis (16 to 45 µm) and the z-axis (6 to 11) (P<.05).

DISCUSSION

The purpose of this study was to evaluate the discrepancy between the definitive cast, the STL-file, and the titanium framework for implant-supported complete-arch prostheses fabricated with selective laser melting (SLM) and electron beam melting (EBM) additive manufacturing technologies. The null hypotheses were accepted, as no statistical significant differences were determined (P>.05).

AM technologies combined with subsequent CNC machining of the implant interface is a current option for fabricating the framework on implant prostheses. To the authors' knowledge, no previous studies have evaluated the implant-prosthesis fit for a complete-arch titanium framework for fixed implant-supported prostheses fabricated with AM technologies.

A contact scanner was used to digitize the definitive cast. The mean distortion between the definitive cast and the STL-file was 1.7 ±0.4 µm on the x-axis, 2.7 ±1.2 µm on the y-axis, 1 ±1 µm on the y-axis, and 3.4 ±2.5 µm for the 3D discrepancy measurements. Similar results were reported in previous studies where the precision of the laboratory dental scanners ranged from 2 to 5 µm.[14-20]

Previous studies have analyzed the implant-prosthesis misfit of the frameworks produced by conventional casting procedures or CNC machining.[12-27] According to Riedy et al,[24] the smallest discrepancy that can be detected by the human eye is between 50 and 100 µm. In the present study, no significant difference was found in the implant-prosthesis discrepancy between the SLM and EBM Ti frameworks. The mean 3D discrepancy was 67 ±13.5 µm for the SLM technology and 60.2 ±18.5 µm for the EBM technology.

The mean discrepancy of the z-axis, representing the occlusogingival discrepancy, for the Ti SLM was 6.2 ±6.1µm and 13.6 ±6.2 µm for the EBM frameworks. Previous studies report a lower distortion on the z-axis compared with the x- and y-axes,[2,24-27] which is consistent with the results of the present study.

An acceptable value for the vertical misfit (z-axis) has been reported to be 10 to 150 µm, but no consensus is presently available.[1-3,61] The vertical misfit determined in the present study ranged from 60.2 ±18.5 µm to 68.6 ±29.7 µm. Thus, these values would be considered clinically acceptable. When an implant-prosthesis discrepancy is greater than 100 µm, the implant-prosthesis discrepancy will be reduced when the prosthesis screws are tightened.[62,63] However increased vertical discrepancies lead to bacterial colonization.[64-66]

For the ability of the manufacturing procedures to replicate the digital design of the metal framework, the comparison between the STL file and the AM frameworks revealed a discrepancy of 39.2 ±27.0 µm on the x-axis, 37 ±14.8 µm on the y-axis, 6.5 ±1.8 µm on the z-axis, and 60.6 ±12.6 µm on the 3D discrepancy analysis. This discrepancy is derived from the accumulated distortion of the manufacturing processes which includes the AM technologies and the CNC machining of the implant interface.

A large standard deviation was found in the present study, indicating that the data points were distributed over a wide range of values. This could be related to the small sample size that could not be increased because of cost considerations, one of the limitations of the study.

The results of the study suggest that the implant-prosthesis discrepancy obtained with the two AM technologies from different manufacturers achieved a fit comparable with that of conventional milling systems with a clinically acceptable implant-prosthesis discrepancy. Further studies are needed with different implant connections, number of implants attached to the frameworks, different framework designs, and implant positions, angulations, and depth. Additional distortion may occur after ceramic or resin application.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Titanium frameworks for complete-arch implant-supported prostheses fabricated using either SLM or EBM additive technologies obtained a clinical acceptable implant-prosthesis discrepancy. Except for the z-axis, the AM titanium frameworks analyzed showed similar implant-prosthesis discrepancy for the x and y-axis. The most favorable results were obtained for the z-axis, representing the occlusogingival direction.
2. The implant-prosthesis discrepancy showed no significant difference between the SLM and EBM additive manufacturing technologies.
3. Both AM technologies, SLM and EBM processes, showed a comparable ability to manufacture the digital design of the metal framework. Except for the z-axis, the AM

titanium frameworks analyzed showed similar discrepancy between the STL-file and the AM frameworks for the x- and y-axis. The most favorable results were obtained for the z-axis, representing the occlusogingival direction.

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TABLES

Table 1. Metal powder composition (manufacturer's data)

Group **Metal powder**	**Composition (wt%)**	
Concept Laser Rematitan	Ti: 90 Al: 6 V: 4	N, C, H, Fe and O <1
Arcam Ti6Al4V ELI	Ti: Balance Al: 5.5-6-5 V: 3.4-4.5 O<0.13	N<0.05 C<0.08 H<0.012 Fe<0.25

Table 2. Mechanical properties of AM titanium (manufacturer's data)

Property	Concept Laser Rematitan	ARCAM EBM
Grade/type	4	5
Density (g/cm^3)	4.5	NA
Tensile strength (MPa)	1005	860
Yield strength (MPa)	950	795
Elongation at fracture (%)	10	10
Young modulus (GPa)	115	114
Hardness (HV)	NA*	NA
Coefficient of thermal expansion	10.16×10^{-6}/ºC	NA
Melting range (ºC)	1604-1655	NA

NA, not available.

Table 3. Distortion between definitive cast and STL file on x-, y-, z-axis and 3D discrepancy values.

Comparison	**X-axis (µm)** Mean ±SD	**Y-axis (µm)** Mean ±SD	**Z-axis (µm)** Mean ±SD	**3D Discrepancy(µm)** Mean ±SD
Definitive cast-STL file	1.7 ±0.4	2.7 ±1.2	1.1 ±1	3.4 ±2.5

SD, standard deviation,

Table 4. Comparison of x-, y-, z-axis and 3D discrepancy values, mean, and standard deviation

Comparison	**X-axis (µm) ±SD**	**Y-axis (µm) ±SD**	**Z axis(µm) ±SD**	**3D Discrepancy (µm) ±SD**
Definitive cast - SLM Frameworks	16.4 ±5.3 a	56.2 ±21 a	6.2 ±6.1 b	60.2 ±18.5 a
Definitive cast - EBM Frameworks	25.1 ±9.9 a	55.3 ±29.4 a	13.6 ±6.2 a	64.8 ±25.3 a
STL – SLM Framework	39.2 ±27 a	37 ±14.8 a	6.5 ±1.8 b	60.6 ±12.6 a
STL – EBM Framework	44.6 ±29.9 a	37.2 ±35.7 a	10.8 ±6.1 a	68.6 ±29.6 a

Similar letters indicate no significant differences for each parameter among the experimental groups tested. SD, standard deviation

FIGURES

Figure 1. A, Complete edentulous mandibular definitive cast. B, Electron bean melting titanium framework. C, Selective laser melting titanium framework.

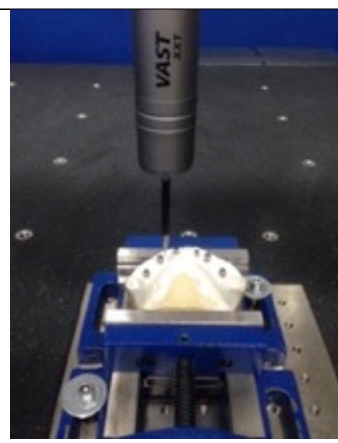
A

B

C

Figure 2. Coordinate measuring machine analysis. A, Of metal framework. B, Of definitive cast.

A



B